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RESEARCH REPORT S-76-2

## LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS

Report 4

### DETERMINATION OF IN SITU DENSITY OF SANDS

by

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August 1977

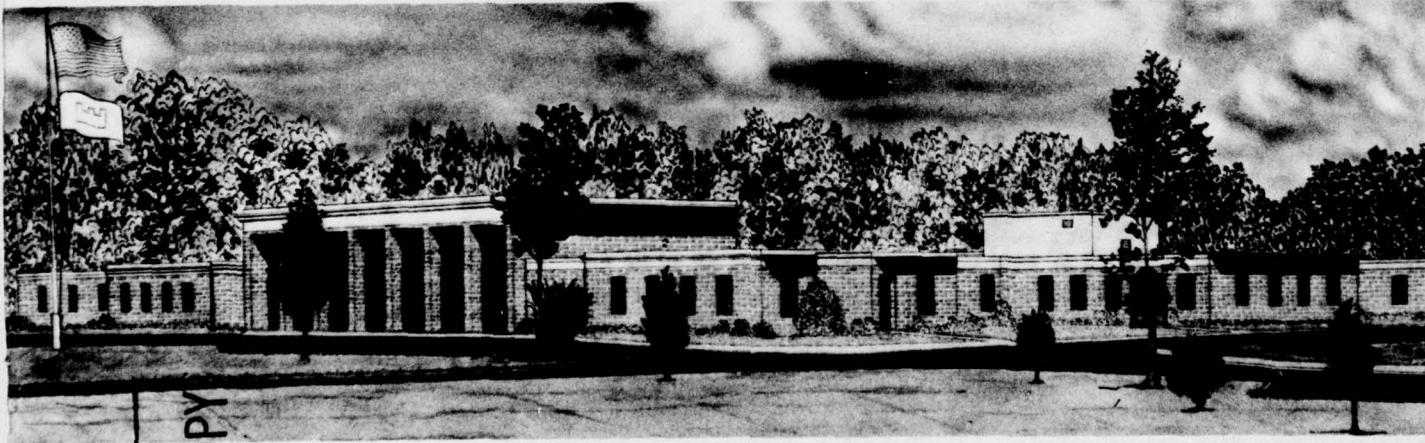
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| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>The use of undisturbed samples to evaluate in situ density and Standard Penetration Test (SPT) to estimate in situ relative density is reviewed. A procedure for obtaining high quality undisturbed samples of sands and the influence of this sampling procedure on the in situ relative density are discussed. The use of radiographs to evaluate sample quality is examined. |   |  |
| As a result of studies reviewed, it is concluded that the SPT is not → over<br>(Continued)   |   |  |

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20. ABSTRACT (Continued).

sufficiently accurate to be recommended for final evaluation of the density or relative density of a site unless site-specific correlations are developed. High quality undisturbed samples of sands may be obtained using a fixed-piston sampler and drilling mud. This sampling procedure yields very good samples in deposits of medium dense sands; however, the procedure tends to densify loose sands and loosen dense sands.

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Preface

This investigation was conducted at the U. S. Army Engineer Waterways Experiment Station (WES) under the sponsorship of the Office, Chief of Engineers, Department of the Army, as a part of Project CWIS 31145, "Liquefaction Potential of Dams and Foundations."

The work was performed and this report was prepared by Dr. W. F. Marcuson III under the general supervision of Dr. F. G. McLean, Chief, Earthquake Engineering and Vibrations Division, and Mr. J. P. Sale, Chief, Soils and Pavements Laboratory. This report is essentially the same as a paper prepared by Dr. Marcuson and submitted to the ASTM Symposium on Dynamic Soil and Rock Testing, Denver, Colo., June 1977.

COL J. L. Cannon, CE, was Director of WES during the preparation and publication of this report. Mr. F. R. Brown was Technical Director.

## LIQUEFACTION POTENTIAL OF DAMS AND FOUNDATIONS

### DETERMINATION OF IN SITU DENSITY OF SANDS

#### Introduction

The accurate and reliable determination of in situ density and in situ relative density of cohesionless soil deposits has plagued civil engineers for decades. These determinations are currently made by indirect or direct techniques. Indirect techniques refer to empirical correlations between index values and relative density. The discussions presented herein will be limited to correlations between Standard Penetration Test (SPT) N values and relative density. In direct techniques the soil weight and volume are measured quantities and the in situ density is directly calculated. The discussion of these methods which is presented herein will be limited to the use of undisturbed samples to determine in situ density and the influence of the sampling procedure on the density determined in the laboratory.

Throughout this paper references will be made to in situ density and in situ relative density. Whenever possible, in situ density will be discussed because of the many problems inherently associated with relative density determinations. Indications (1-7) are that even if the in situ density of a soil deposit is known, the accuracy with which the relative density can be obtained is of the order of  $\pm 20$  percent. This scatter is associated with difficulties in obtaining accurately the minimum and maximum densities required to compute the relative density. As a matter of practice, the U. S. Army Engineer Waterways Experiment Station (WES) uses in situ density whenever possible, and

resorts to the use of in situ relative density only when it is necessary to compare different materials or different sites.

#### Indirect Determination of In Situ Relative Density

The Bureau of Reclamation has reported results (8,9) which correlate relative density with SPT N values and overburden pressure.

These correlations were based on data obtained from laboratory penetration tests conducted in tanks filled with sand. Bazaraa (10) also developed correlations between SPT N values, overburden pressure, and relative density. These correlations were based on field data and are more conservative than the curves developed by Gibbs and Holtz (8).

In the interest of brevity, a discussion on the history of the use of the SPT to estimate relative density has been omitted. If the reader is interested in this he is referred to deMello (11). However, a brief summary of the results obtained at WES in a recent laboratory study of the SPT is included. The details are presented elsewhere (12-15).

During this WES study, SPT's were performed on 4-ft-(1.2-m)diam by 6-ft-(1.8-m)high samples of four sands (Reid Bedford Model sand, Ottawa sand, Platte River sand, and Standard Concrete sand) at various relative densities under overburden pressures up to 80 psi ( $5.52 \text{ kN/m}^2$ ). Figure 1 shows the grain size distribution curve and other pertinent data for each of these sands. Figure 2 is a plot of N values versus relative density which were obtained by WES for the Reid Bedford Model and Ottawa sands. Data points are plotted on this figure for overburden pressures of 10, 40, and 80 psi (69, 276, and

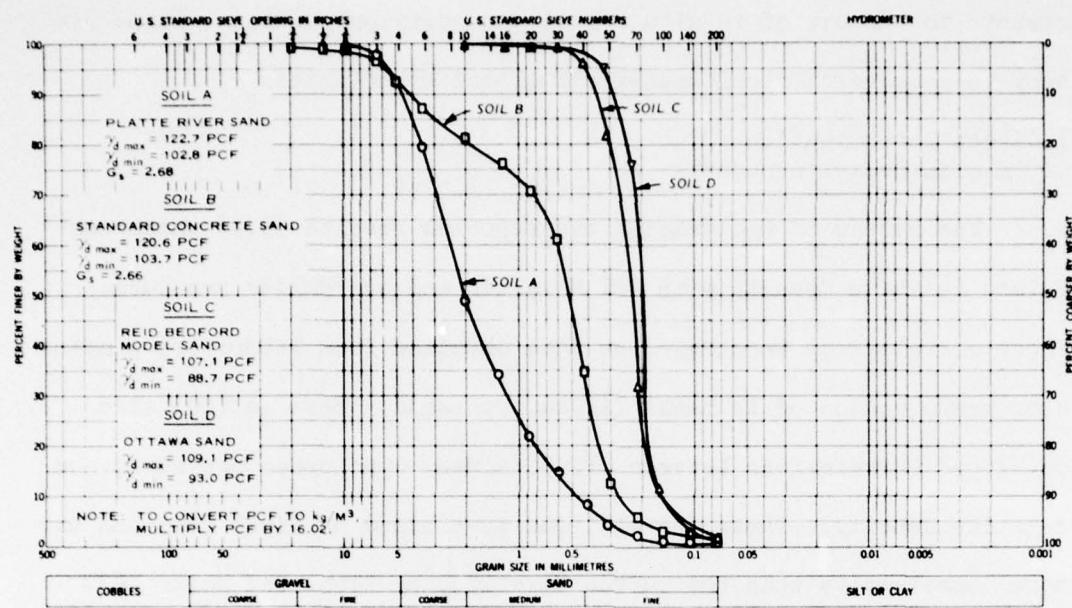


Figure 1. Mechanical analyses and density values for Platte River, Standard Concrete, Reid Bedford Model, and Ottawa sands

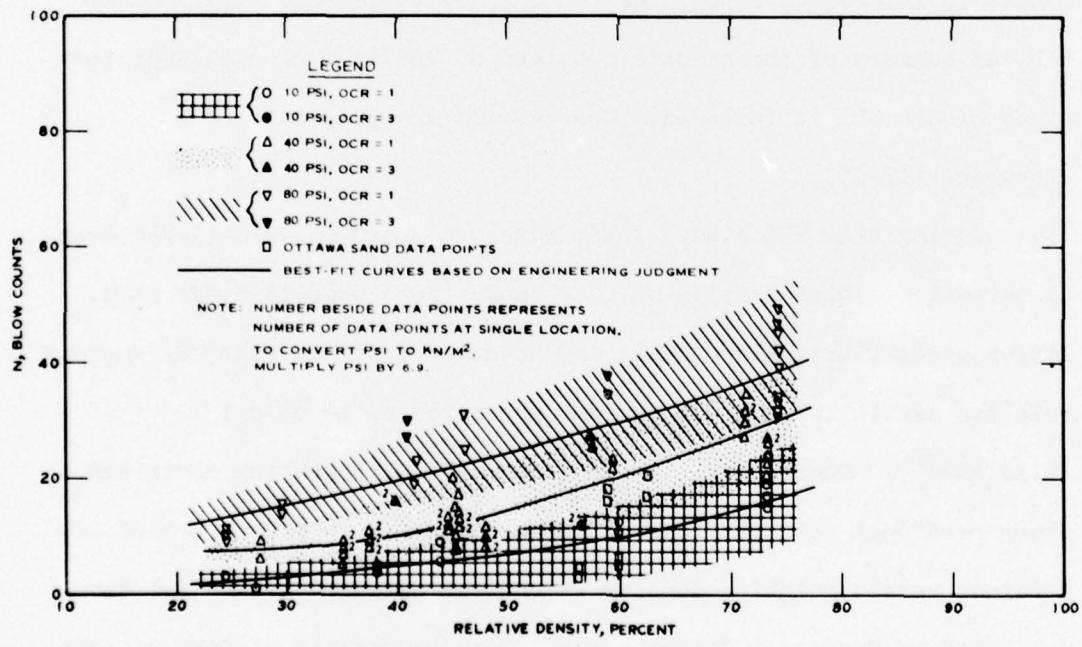


Figure 2. WES SPT data for Reid Bedford Model sand and Ottawa sand for three overburden pressures

552 kN/m<sup>2</sup>) and overconsolidation ratios (OCR) of 1 and 3. This figure depicts the spread of data for three overburden pressures under ideal laboratory conditions. As can be seen, for a given overburden pressure and N value, the spread in the relative density is about  $\pm 15$  percent.

Figure 3 presents the same data spread with the Gibbs and Holtz and Bazaraa curves superposed for comparison purposes.

Figure 4 is a plot of N values versus relative density for WES tests on Platte River and Standard Concrete sands. Figures 2, 3, and 4 indicate that a simple family of curves relating SPT N values, overburden pressure, and relative density for all sands under all conditions is valid.

After discarding unreliable data, a statistical analysis was performed on data obtained from testing all four sands. The equation developed to best describe the data is:

$$D_r = 11.7 + 0.76 \left[ (222)N + 1600 - 53(\bar{\sigma}_v) - 50(C_u)^2 \right]^{1/2}$$

where

$D_r$  = relative density, percent,

N = SPT blow counts, blows per foot,

$\bar{\sigma}_v$  = effective overburden pressure, psi,

$C_u$  = coefficient of uniformity.

This equation fits the data obtained on normally consolidated material with a coefficient of correlation ( $r^2$ ) of 0.85 and a standard deviation ( $\pm\sigma$ ) of 8.3 percent.

The significant conclusions reached in this laboratory penetration test study were as follows:

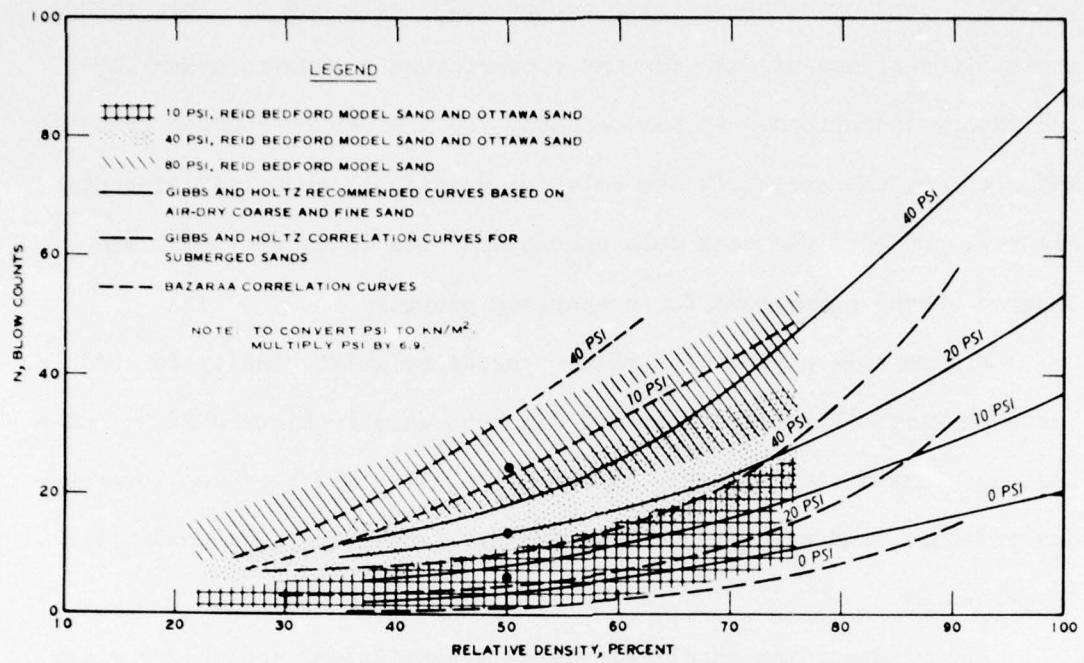


Figure 3. Comparison of WES data, Gibbs & Holtz correlation curves, and Bazaraa curves

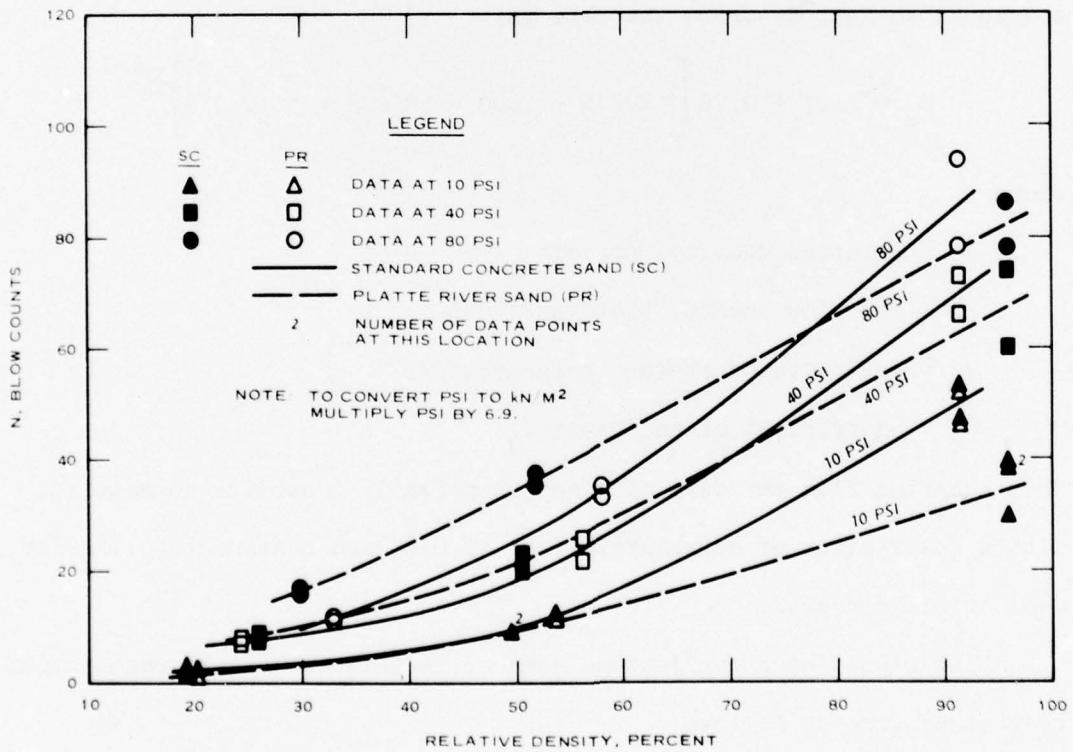


Figure 4. WES SPT data for Platte River and Standard Concrete sands

a. Based on a comparison between the correlations presented by Bazaraa, Gibbs and Holtz, and WES, it was concluded that the SPT is not sufficiently accurate to be recommended for final evaluation of the density or relative density at a site, unless site-specific correlations are developed. However, the SPT does have value in planning the undisturbed sampling phase of the subsurface investigation and in comparing different sites.

b. Sand type and specimen preparation technique influence penetration resistance.

c. The spread of data derived from testing four sands under optimum laboratory conditions suggests that a simplified family of curves correlating SPT N values, relative density, and overburden pressure for all cohesionless soils under all conditions is not valid.

d. The expression derived from the statistical analysis is based on data obtained under laboratory conditions and therefore has limited application. It does not adequately address the variability of subsurface conditions found in the field. Water table conditions, overconsolidation, length and weight of drill rods, and dynamic interaction of the drive-sampling system were either not intensively studied or were not investigated. Additional research is required to evaluate these factors.

#### Direct Determination of In Situ Density

As previously defined, direct determination of in situ density means a process in which the weight and volume of the soil are measured and density is easily calculated. It is generally accepted that there

is no such thing as a truly undisturbed sample of soil. Samples that are routinely referred to as "undisturbed" samples are high quality samples obtained with minimal disturbance. The question that remains is: How does this minimal disturbance affect the density determinations based on weight and volume measurements made in the laboratory.

#### Development of the Sampling Procedure

Over the past three decades WES has conducted various studies with the objective of evaluating various sampling techniques for determination of in situ density (16-20). During the late 1940's a drilling, sampling, and handling procedure was developed which yields high quality undisturbed samples (16). The drilling procedure uses a fishtail bit with baffles. These baffles are welded on the bit below the jets to block the downward flow of drilling mud which might otherwise disturb the sand to a considerable depth below the bit. The sampling procedure involves the use of a fixed-piston type sampler known as the Hvorslev sampler. The drilling and sampling procedures, including starting and advancing the boring, sampling, withdrawal operation, and treatment of samples, are described in detail in Reference 16. Using this procedure, the sample is withdrawn from the borehole, held in a vertical position, and the sampler and 3-in.-ID(7.62-cm) thin-walled sampling tube are disconnected. The tube is maintained in a vertical position while a perforated expanding end packer is placed in the bottom of the sample tube. The tube is placed in a rack in the vertical position and allowed to drain. The time required for proper drainage varies from 24 to 48 hours depending on the amount and character of

fines in the soil samples. After drainage is completed an expanding end packer is placed in the top of the sample tube. If the sample is to be used only for density determinations, it is rotated into the horizontal position and placed in a cradle. The top of the tube is marked and the top side of each tube is then struck 50 light blows with a rubber hammer, starting at one end of the tube and working toward the other with 25 blows and then reversing the procedure, thereby consolidating the sand and preventing possible liquefaction and flow of any loose samples of sand in the tube during transportation to the laboratory. The tubes are prevented from rotating during transportation. In the laboratory, samples are cut into 3-in.(7.62-cm) increments with a band saw and unit weight determinations made by conventional methods for each increment of sample. The total volume of the section of tube from which the sample increment is removed is used as the basic volume for the sample increment in all unit weight determinations.

It is important to note that once the sample is extracted from the borehole its treatment depends on whether an undisturbed sample of the material is desired for laboratory testing or in situ density is the only desired end product. Only if in situ density is the desired end product is the sample tapped, thus disturbing the soil sample.

This sampling procedure is used routinely by the WES and has been used effectively during the subsurface investigations for at least three building sites in Canada (21).

#### First Investigation

The density changes caused by the above sampling procedure were studied at WES in the early 1950's (17). In this study, two sands, one

medium (MR1) and one fine (MR2), were placed in a 2-1/2-ft-(0.75-m)diam  $\times$  6-ft-(1.8-m)deep drum at high and low initial densities. The grain size distributions are shown in Figure 5. The sand was sampled using

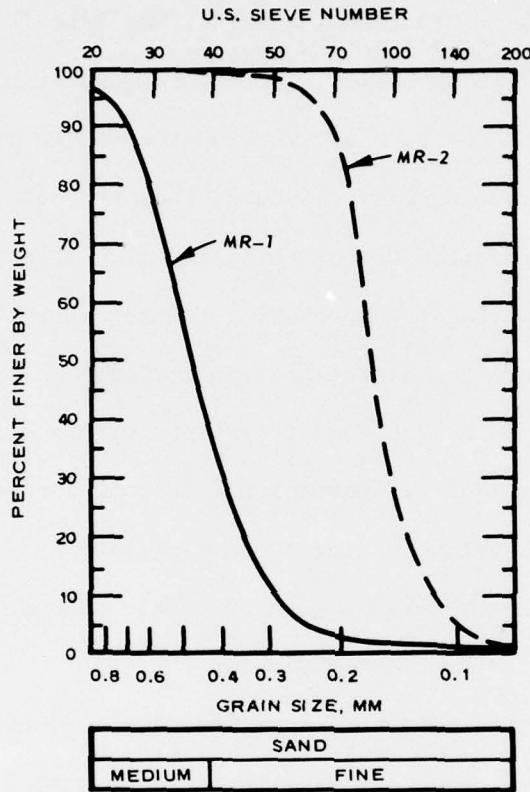
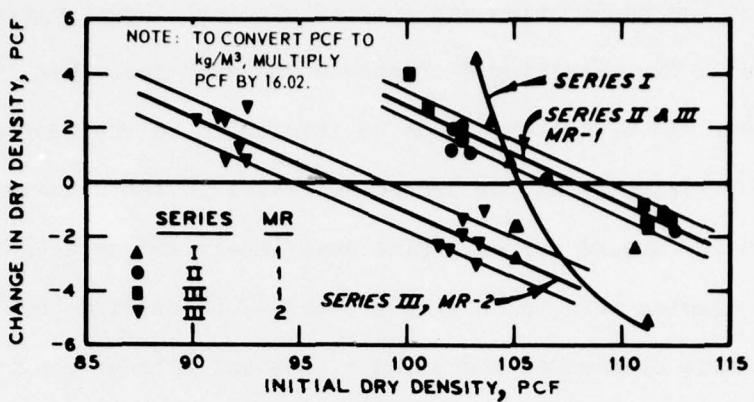


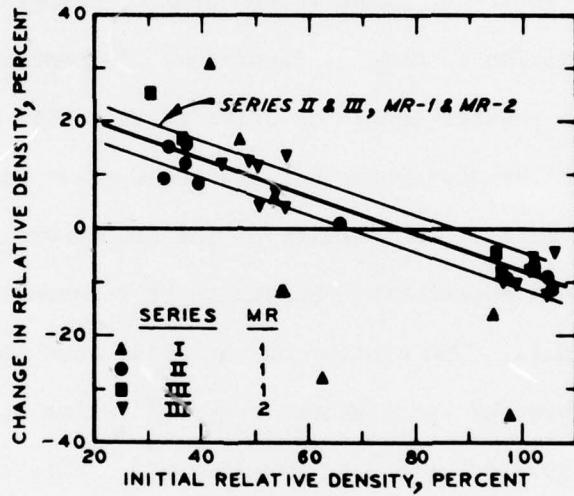
Figure 5. Mechanical analyses of two Mississippi River sands

a fixed-piston type sampler with lacquered thin-walled seamless steel Shelby tubes. These samples were not tapped but were carefully transported to the laboratory where incremental distribution of density within the sample was determined using all possible precautions to avoid additional disturbance of the sample.

The average density changes obtained are illustrated in Figure 6. The change in density versus initial density is plotted in Figure 6a.



a. CHANGE IN DENSITY VERSUS DRY DENSITY



b. CHANGE IN RELATIVE DENSITY VERSUS  
INITIAL RELATIVE DENSITY

Figure 6. Average density changes caused  
by sampling

The greatest density changes were obtained in the first series of tests using the medium sand (MR-1). The samples were taken with a 2.875-in.- (7.3-cm)diam sampler having comparatively large clearances. High rates of penetration, depths of penetration equal to 2 to 2.3 ft (0.6 to 0.7 m) and no surcharge loads were used. The same sand was used in the second series of tests, but the clearance was reduced to

0.50 percent and penetration was stopped when settlements appeared to be excessive. The resulting disturbance was much less than in the first series. No trends which can be attributed to the controlled variation of equipment and/or procedures exist in the density changes obtained in the second series. Fine sand (MR-2) was used in the third series and samples were taken with a 3-in.- (7.62-cm)diam sampler having variable clearances and using a constant rate of penetration. The average density changes are similar to those obtained in the second series of tests. No trends exist in the density changes which can be attributed to variation in sampler clearance. In comparison with the second series, the greater length of drive in the third series appears to result in a greater disturbance of the loose material. Statistical correlations were made of the results of the second and third series. The results of these correlations appear to be reasonable even though based on limited data. The scatter of the data about the line of regression, as measured by the standard error of estimate,  $S$ , is in the order of  $\pm 0.5$  to  $\pm 0.7$  pcf ( $\pm 8.0$  to  $\pm 11.2$  kg/m<sup>3</sup>). This scatter corresponds to the average density changes caused by the laboratory density determination procedures discussed earlier. It seems reasonable to assume that the scatter obtained in the second and third series of tests was caused by inherent errors in laboratory procedures and is large enough to mask any density changes caused by controlled variation in sampling equipment and procedures.

The results of all tests are plotted in Figure 6b as changes in relative density versus initial relative density. The combined effects

of sampling and testing tended to cause a decrease in average density for initial relative densities of greater than 77 percent and an increase in relative density for lesser initial values in the second and third series. The scatter expressed as a standard error of estimate,  $S$ , amounts to  $\pm 3.5$  percent (in terms of relative density). The change in average relative density is large, 10 to 15 percent, at extremely high and low values of initial relative density.

#### Second Investigation

Because the influence of overburden pressure was not adequately addressed in the first study, a second investigation was conducted at WES during the late 1950's (18). During this study, two Mississippi River sands (Sands 1 and 2 in Figure 7) were placed in a 3-1/2-ft-(1.07-m)diam by 6-1/2-ft-(1.98-m)deep cylindrical tank at relative densities of approximately 20 percent and 90 percent. Surcharge pressures of 30, 60, and 100 psi (207, 414, and 690 kN/m<sup>2</sup>) were applied to the samples. After consolidation, 3-in.(7.62-cm) undisturbed samples were taken using the Hvorslev fixed-piston sampler. Figure 8 summarizes the pertinent results and gives corrections for the change in density caused by sampling. The correction factor curves are plotted in Figure 8a. Lines shown to indicate the correction factors for relative density at 10 percent intervals between 30 and 86 percent were spaced by linear proportion. The plot of density correction for overburden pressure indicates that at overburden pressures ranging from 20 to 50 psi (138 to 345 kN/m<sup>2</sup>) the density corrections for Sand 1 at a measured relative density of 30 percent range from -1.2 to -1.6 pcf (-19.2 to -25.6 kg/m<sup>3</sup>) and for a measured relative density of 86 percent the

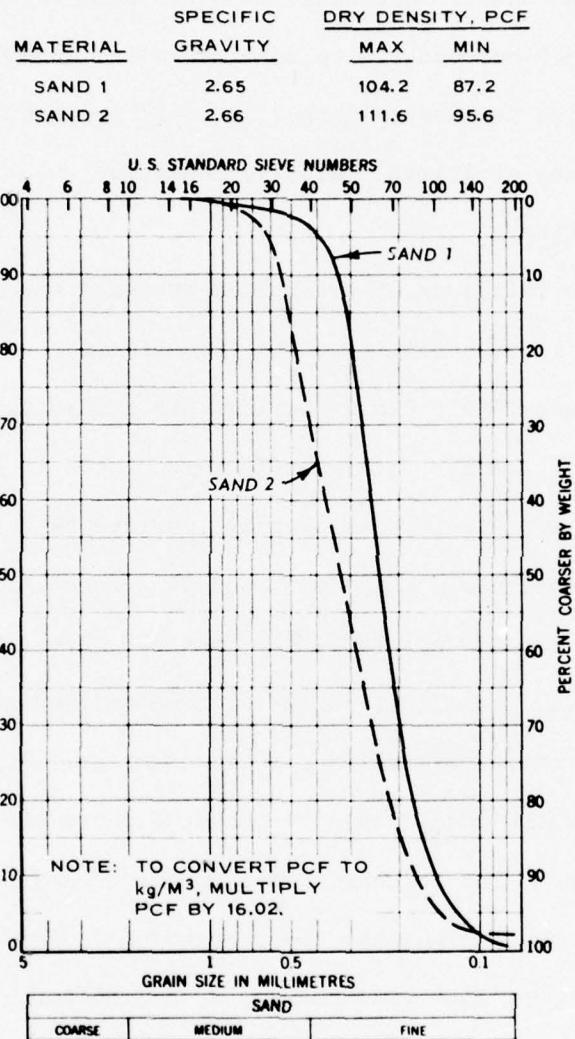
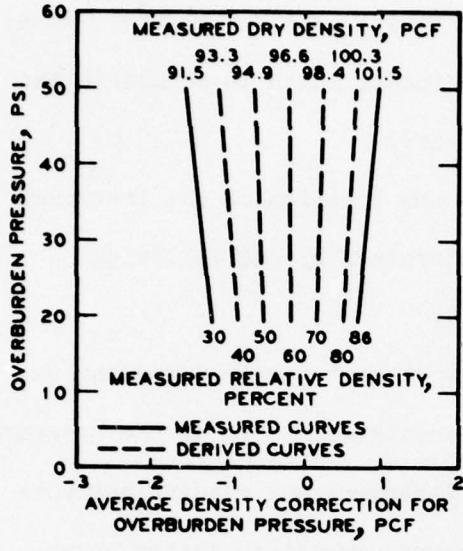
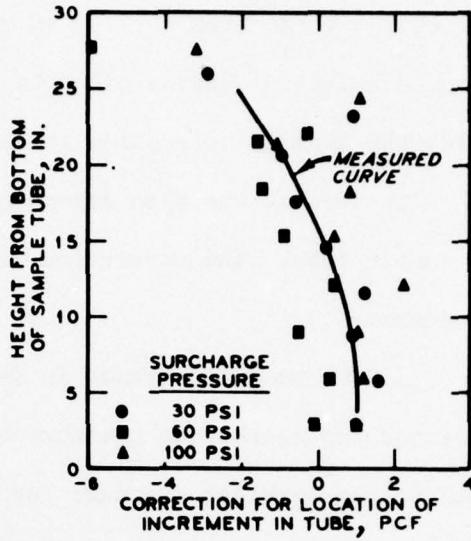


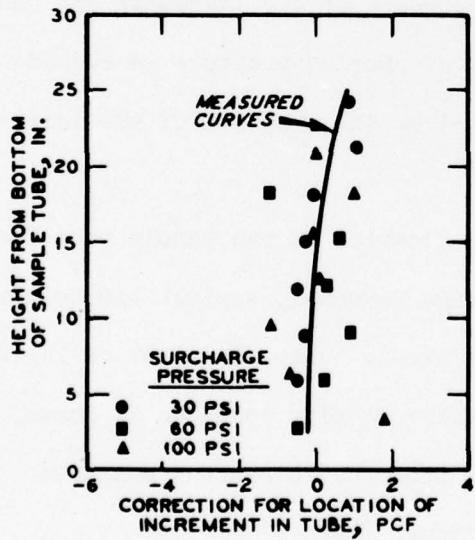
Figure 7. Mechanical analyses and density values for Sands 1 and 2



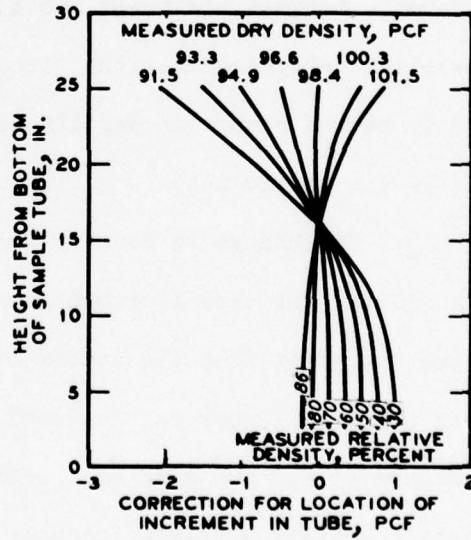
a. DENSITY CORRECTION FOR  
OVERBURDEN PRESSURE, SAND 1



b. DENSITY CORRECTION FOR LOCATION  
IN SAMPLE TUBE, SAND 1 PLACED AT 30%  
MEASURED RELATIVE DENSITY



c. DENSITY CORRECTION FOR LOCATION  
IN SAMPLE TUBE, SAND 1 PLACED AT 86%  
MEASURED RELATIVE DENSITY



d. DENSITY CORRECTION FOR LOCATION  
IN SAMPLE TUBE, COMBINED PLOT

NOTE: TO CONVERT PSI TO KN/M<sup>2</sup>, MULTIPLY PSI BY 6.9.  
TO CONVERT PCF TO kg/M<sup>3</sup>, MULTIPLY PCF BY 16.02.  
TO CONVERT IN. TO CM, MULTIPLY IN. BY 2.54.

Figure 8. Corrections for change in density caused by sampling for Sand 1

corrections range from +0.7 to +0.9 pcf ( $+11.2$  to  $+14.4 \text{ kg/m}^3$ ). At a measured relative density of about 60 percent, which is common in the field, the density correction is almost zero.

The density was also dependent on the location of the increment in the sample tube. The correction was determined by the following procedure:

a. The measured change in density of each sample increment was corrected for overburden pressure by entering Figure 8a at the pressure equal to the vertical pressure for the increment and reading horizontally across to either the 30 or 86 percent correction factor curve, depending on the measured density of the sample increment, and then reading vertically down to the average density correction scale. The difference between the total change in density of the increment and the correction determined for the effect of overburden pressure is considered to be the change in density effected by the location of the increment in the sample tube.

b. The change in density for the location in the sample tube was then plotted for each increment, with sign reversed, against the height of the increment from the bottom of the sample tube. The plot of increments from the 30 percent measured relative density specimen is shown in Figure 8b and the plot of increments from the 86 percent measured relative density specimen is shown in Figure 8c.

c. Smooth curves were drawn through the points. These smooth curves were then combined in a single plot, shown in Figure 8d, and curves for measured relative densities of 40, 50, 60, 70, and 80 percent were drawn by linear proportion between the 30 and 86 percent

relative density curves. The corresponding dry densities are given for each relative density curve.

The plot of density correction for location of increment in the sample tube, for Sand 1 at a measured relative density of 30 percent, indicates that at heights greater than about 24 in. (61 cm) in the tube, the density change is rather large and the data are quite scattered. This fact suggests that densities of increments at heights greater than 24 in. (61 cm) in the tube should not be considered reliable. Also, although density changes in the bottom 6 in. (15.2 cm) of the 30-in.- (76.2-cm) long sample tubes were not excessive, it must be pointed out that the samples of the tank specimens were not pulled from the tank immediately after the sampler drive had ended, but were removed from the specimen after all three sample tubes had been pushed and the material excavated from around the tubes. If the sample tubes had been pulled out immediately, as is necessary in the field, it is believed that the density changes in the bottom 6 in. (15.2 cm) would have been larger because of stress changes in the vicinity of the bottom of the sampling tube. Therefore, in the analysis of density measurements on samples obtained in the field, data from heights greater than 24 in. (61 cm) and lower than 6 in. (15.2 cm) should be disregarded and only data from the central 18 in. (45.7 cm) should be used for determining densities.

The combined plot of density correction for locations of increments in the sample tube for Sand 1 (Figure 8d) indicates that at heights from 6 to 24 in. (15.2 to 61 cm) in the sample tube, the density correction for 30 percent measured relative density ranges from +1.0 to

-1.8 pcf ( $+16$  to  $-28.8 \text{ kg/m}^3$ ), and for 86 percent measured relative density the correction ranges from -0.2 to +0.7 pcf ( $-3.2$  to  $+11.2 \text{ kg/m}^3$ ). At a measured relative density of 60 percent, a density commonly found in the field, the density correction depending on height in the tube ranges from +0.3 to -0.5 pcf ( $+4.8$  to  $-8.0 \text{ kg/m}^3$ ).

Considering density corrections for both overburden pressure and location in sample tube, the total density correction could be as large as -3.4 pcf ( $-54.5 \text{ kg/m}^3$ ) for a measured relative density of 30 percent at an overburden pressure of 50 psi ( $345 \text{ kN/m}^2$ ) and height of 24 in. (61 cm) in the sample tube, and as large as +1.7 pcf ( $+27.2 \text{ kg/m}^3$ ) for a measured relative density of 86 percent at an overburden pressure of 50 psi ( $345 \text{ kN/m}^2$ ) and a height of 24 in. (61 cm) in the sample tube. However, for conditions which are commonly encountered in the field (e.g., relative densities ranging from 30 to 80 percent, and overburden pressures ranging from 20 to 40 psi ( $138$  to  $276 \text{ kN/m}^2$ )), with heights of increments in the tubes ranging from 6 to 20 in. (15.2 to 50.8 cm), the maximum total density corrections would range from -2.3 to +0.8 pcf ( $-36.9$  to  $+12.8 \text{ kg/m}^3$ ), with a more common average correction range of -1.2 to 0.6 pcf ( $-19.2$  to  $9.6 \text{ kg/m}^3$ ).

Since the difference between maximum and minimum densities as determined by laboratory tests generally ranges from about 16 to 20 pcf ( $256.3$  to  $320.4 \text{ kg/m}^3$ ) for various sands, a density correction of approximately 1.0 pcf ( $16 \text{ kg/m}^2$ ) would amount to a change in relative density of about 5 to 6 percent. Based on a limited evaluation of results of tests on Sand 2, it appears that correction factors for

other sands might be approximately 1 pcf ( $16 \text{ kg/m}^3$ ) greater than correction factors for Sand 1 (i.e., an average of about 2 pcf ( $32 \text{ kg/m}^3$ )).

### Third Investigation

Recently (1974-76) another series of tests was conducted on Reid Bedford Model sand in a 4-ft-(1.2-m)diam by 6-ft-(1.8-m)high stacked ring facility (19, 20). The purpose of the stacked rings is to significantly reduce sidewall friction so that the sand sample has a more realistic stress gradient. Dry sand was placed in a stacked-ring facility, submerged, and then an overburden pressure was applied. Finally the sand was sampled using the WES procedure. Figure 9 is a comparison of placed density, corrected for the effects of consolidation under the applied vertical loadings, with sampled density. These data show considerable scatter and are difficult to interpret. The linear regression fit to the data is aligned fairly close to the line of perfect sampling, and crosses the perfect sampling line at a relative density of about 36 percent, which is considerably less than the relative density of 77 percent reported in Reference 17 and shown in Figure 6, but the trend is the same. This variation may be attributed to (a) scatter in the data which made precise interpretation impossible, (b) differences in the sands tested (such as gradation, percent fines, and angularity) and (c) differences in the methods of sample preparation. The principal results and conclusions drawn from this study (19) are:

- a. It was noted that the placed density at the time of sampling probably varied from +2.9 to -1.5 pcf (+46.4 to -24  $\text{kg/m}^3$ ) from the measured values.

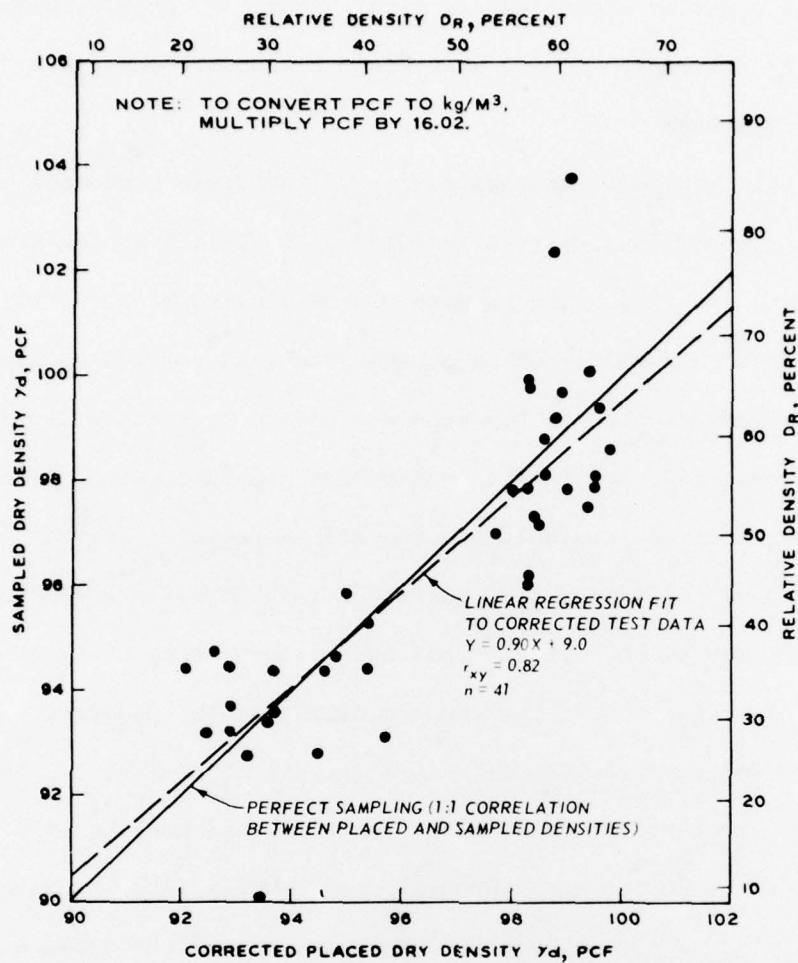


Figure 9. Comparison of placed density corrected for applied overburden pressure with sampled density

b. The sampled versus placed density comparisons presented suggest that sampling accuracy using the techniques described is within  $\pm 3.4$  pcf ( $\pm 54.5 \text{ kg/m}^3$ ) for 95 percent of the sampling conducted at relative densities ranging from 20 to 60 percent. However, it can also be concluded that a more meaningful assessment of the sampling accuracy could have been made had it been possible to exercise better placed density control during the study. It is very probable that in this

event the apparent accuracy of sampling would have shown corresponding improvements.

Despite the uncertainties cited, this and the preceding studies indicate that sampling with a tube sampler tends to densify loose sand and to loosen dense sands. More definitive conclusions regarding the influence of tube sampling on the accuracy of density determinations cannot be advanced because of the uncertainty associated with the placed density results uncovered in this study, and which probably existed in the previous studies.

#### The Use of Test Pits

The results of all the studies discussed above indicate that good samples can be taken in medium dense material. However, the sampling procedure causes significant disturbance in either loose or dense deposits. Consequently, it may appear desirable to obtain undisturbed samples from test pits instead of boreholes whenever an extremely loose or dense deposit is encountered. The reader is cautioned that consolidation caused by the lowering of the groundwater table and shear stresses imposed during excavation may have an influence on the density that is larger than that experienced by sampling. Settlement markers should always be installed prior to excavation so that the effects of lowering the groundwater table may be evaluated. The equipment shown in Figure 10 lends itself to obtaining high quality undisturbed samples in test pits. This equipment, developed by Geotechnical Engineers Incorporated (GEI), Winchester, Mass., consists of a tripod holder and a 3-in.- (7.6-cm)diam brass Denison tube. The details of its use and



Figure 10. Undisturbed sampler being used in a test pit  
(courtesy of GEI)

operation are presented in Reference 22. The sampling procedure involves trimming the soil carefully for a distance of about 1/8 to 1/4 in. (0.3 to 0.6 cm) ahead of the tube to a diameter slightly larger than that of the tube. Then light (a few pounds) vertical pressure by hand is used to advance the tube and the cutting edge shaves off the excess soil. This procedure is repeated until the desired sample length is recovered. Indications are that this sampling procedure also tends to loosen dense materials by an average of approximately 2 pcf ( $32 \text{ kg/m}^3$ ) and extreme values may be as large as 4 pcf ( $64 \text{ kg/m}^3$ ). Thus when a dense and possibly a loose deposit is encountered, test pits may not provide better undisturbed samples than borings; however, they do provide a bulk of high quality additional data unobtainable from borings. For this reason test pits may be desirable.

### Evaluation of Sample Quality

If one assumes a uniform thickness of sample tube and a uniform thickness of a homogeneous sample, then the density of the sample is roughly proportional to the film density of an X-ray, c.f., Krinitzsky (23). Figure 11 shows a radiograph of an alluvial sand sample obtained with a Hvorslev fixed-piston sampler. Also shown is a plot of film density through the center line of the core. This technique has been used on several studies by WES (24-26) to evaluate qualitatively sample variation, layering, and disturbance.

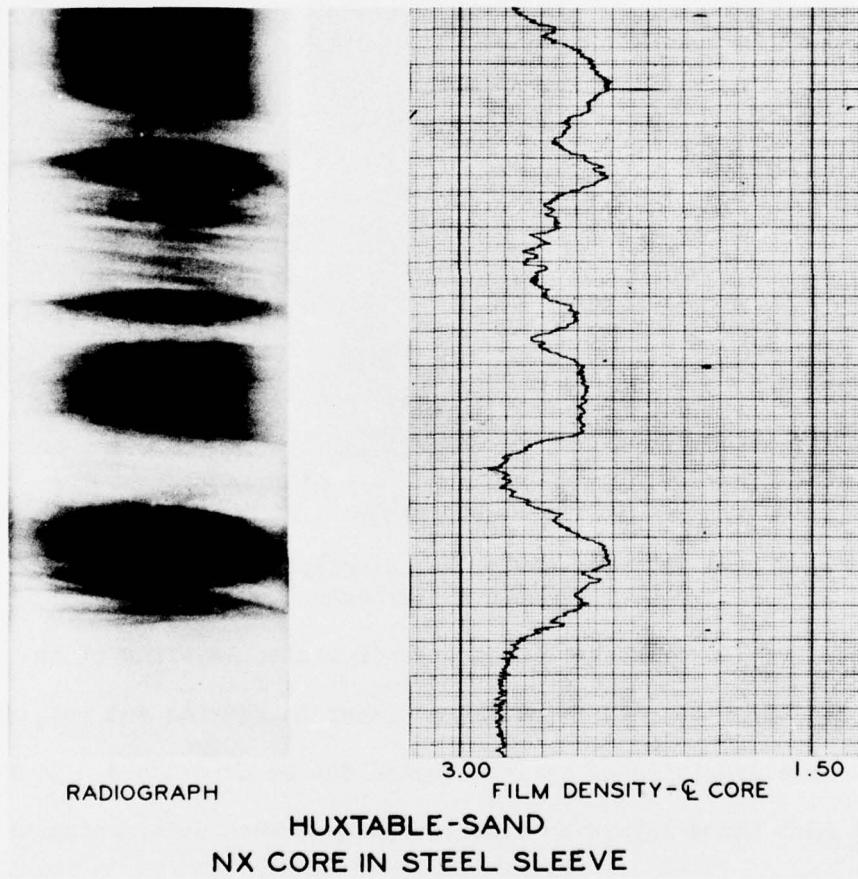


Figure 11. The use of X-radiograph film density to determine the density of soil samples

Figure 12 shows radiographs of both high quality and low quality undisturbed samples. Notice that in the high quality samples the bedding planes can be seen all the way to the sample edge. In the low quality sample these planes are contorted, indicating disturbance.

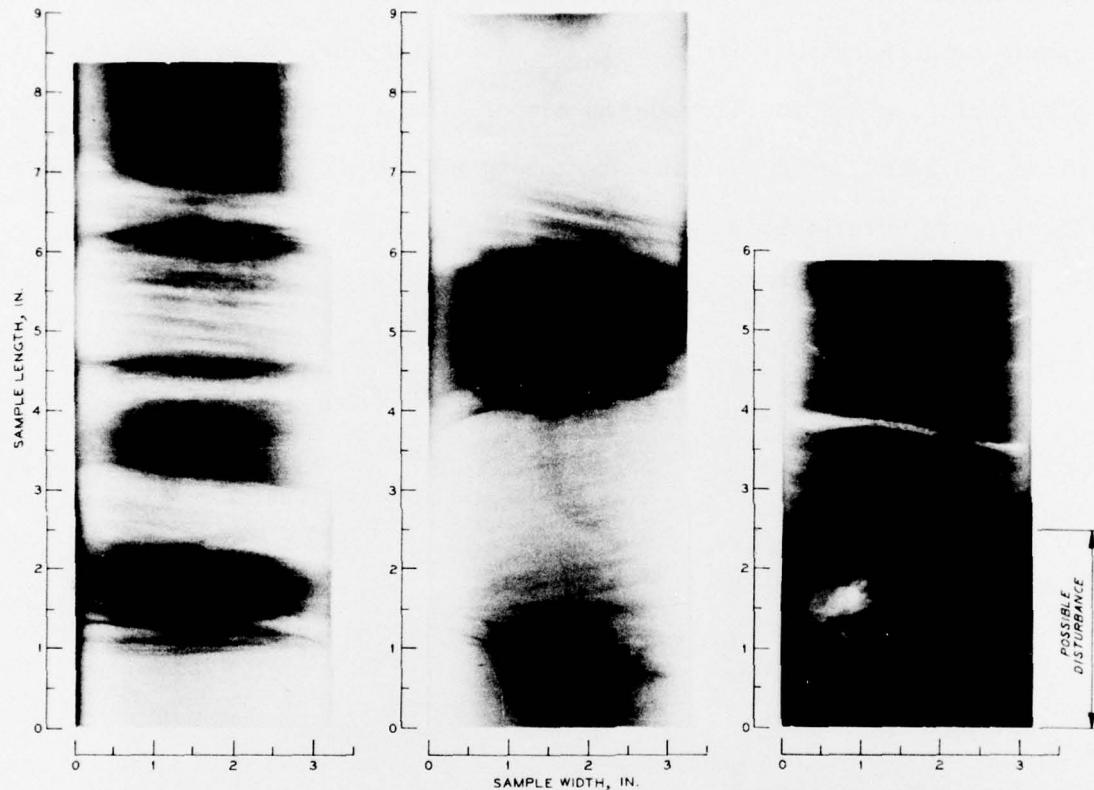


Figure 12. The use of X-radiography to evaluate sample disturbance

Visual observation of these radiographs indicates layering of the deposit and the tubes can be marked at layer boundaries and cut, so that absolute densities of various layers can be determined. It is critical that these layers be kept independent when determining absolute and relative density because the mixing of materials will change the gradation and this can change the maximum and minimum density

determinations considerably (27). As stated previously, WES prefers to use absolute density or relative density whenever possible.

Research currently in progress at WES has as its objective the accurate and reliable determination of soil moisture and density from undisturbed samples (28). The process involves the use of Californium 252 to determine bulk density and water content. Preliminary results indicate that an accurate determination of bulk density and water content is feasible in the foreseeable future.

#### Conclusions

Based on the work summarized herein the following conclusions can be drawn:

a. The SPT is not sufficiently accurate to be recommended for final evaluation of the density or relative density at a site unless site-specific correlations are developed. However, the SPT does have value in planning the undisturbed sampling phase of the subsurface investigation and in comparing different sites. The empirical correlation of SPT N value versus  $D_r$  derived from the statistical analysis does not adequately address the variability of subsurface conditions found in the field. Water table conditions, overconsolidation, length and weight of drill rods, and dynamic interaction of the drive-sampling system were either not intensively studied or were not investigated. Additional research is required to evaluate these factors.

b. High quality undisturbed samples of sands can be obtained using a fixed-piston sampler and drilling mud. This sampling procedure yields very good samples of medium dense sand, but tends to densify loose

sands and loosen dense sands. This disturbance appears to be a function of relative density, overburden pressure, and position in the sample tube. This disturbance may cause the sample density to be in error by as much as 4 pcf ( $64.1 \text{ kg/m}^3$ ) in extreme cases.

c. The sampled versus placed density comparisons presented suggest that the sampling accuracy using the techniques described is within  $\pm 3$  pcf ( $\pm 48 \text{ kg/m}^3$ ) most of the time; however, it can also be concluded that a more meaningful assessment of sampling accuracy could have been made were it possible to exercise better placed density control during the studies.

d. The use of radiographs is an adequate and reliable way of determining the layering of the sample inside the tube and the degree of sample disturbance.

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